ENGINEERING NEWS REPRINTS .25 Cents

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Ignitions and Explosions in the Discharge Pipes and Receivers of Air Compressors

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(Reprinted from Engineering News, March 2, 1905)

PRICE 25 CENTS

NEW YORK
THE ENGINEERING NEWS PUBLISHING CO.

GENERAL

IGNITIONS AND EXPLOSIONS IN THE DISCHARGE PIPES AND RECEIVERS OF AIR COMPRESSORS.

Ignitions and explosions in the discharge pipes and receivers of air compressors are by no means uncommon. The increasing use of compressed air at higher and higher pressures, together with the general ignorance on the part of the men in charge of the machines, as to how and why such accidents occur, make it probable that they will continue to occur with greater frequency. For very obvious reasons the manufacturers say as little as possible about the subject to prospective buyers. It cannot be expected that the men in charge at the time of accident will make any report that will reflect upon themselves. So it happens that in but comparatively few cases of these accidents have the results of careful investigation been given to the public at large.

From an examination of about twenty accidents, of which more or less complete data have been gathered, a clear conception of the causes has been formed, from which may be drawn definite conclusions as to the means of prevention. In a number of the cases examined serious explosions have occurred, resulting in fire and death; in others, simply ignition, or burning out, with no other damage than that to pipe joints and gaskets. One case of a Bessemer blowing engine is reported where the pipes have been red hot on

several occasions and been allowed to burn out. In another case the ignition so vitiated the air that was being sent into a mine that men were asphyxiated. The report upon a very serious explosion states that "the air in the discharge pipe first caught fire and then exploded," it having been observed before the explosion that the pipe was red hot.

It would be out of place in this discussion to mention the location of these accidents or the makes of the compressors. Such reference might be construed as reflecting on the maker or the management. Furthermore, some of the information upon which this article is based was given with the understanding that no names or places should be mentioned.

These accidents are not confined to any one type of compressor, nor are they confined to cases where the terminal gage pressure is unusually high. It is in the discharge pipe and receiver that the trouble occurs, and in most cases the compressor escapes without injury. Rarely, if ever, does the explosion take place immediately in the cylinder. One case is reported where the cylinder head was blown off, killing the man who was examining the discharge valves, but even in this case the evidence does not prove that the explosion did not originate in the receiver. It is unfortunate that we have not the testimony of that man as to the condition those valves were in at the time, for, as will be shown later on, they were probably the immediate cause of the explosion.

It is perfectly evident that just before such an accident there must be something to burn, in the discharge pipe or receiver, and a temperature sufficiently high to ignite it. Accumulation of combustible matter, together with a terminal temperature at the end of a compression stroke suf-

ficient to start combustion, accounts for the cases of ignition; the presence of a gas or vapor, forming an explosive mixture with the air, with a temperature equal to the burning point of the vapor at the pressure, accounts for the cases of explosion. Where, as is reported in a few cases, ignition has preceded explosion, it is clear that in the first place there was a sufficient temperature to start combustion, and then there was driven off a gas or vapor, and this, mingling with the air in suitable proportions, formed an explosive mixture. We have, then, to inquire as to the origin and nature of the combustible matter and to the causes and conditions that tend to produce excessively high temperature.

ORIGIN AND NATURE OF THE COMBUSTIBLE MATTER.

Some lubrication of the air cylinder is necessary, and, as was to be expected, the combustible matter is found upon examination to be derived from the lubricant used together with dust from the air. It is around collieries that a majority of these accidents have occurred, but enough have occurred where the air was practically free from dust to make it clear that while dust, and especially coal dust, undoubtedly adds an element of danger, it is not the prime source. In the character and quantity of the lubricant used must be located the first cause of the trouble. The dust aggravates a condition first produced by the lubricant, and the lubricant assists the dust to deposit. One report from a colliery mentions that the walls of the receiver were coated an inch thick with a caked mass of dust and oil, which caught fire and burned out without producing an explosion. In another case, after the discharge pipe had been wrecked by an explosion, the deposit on the re-

ceiver walls was found to be 2 ins. thick. These deposits were no doubt the accumulation of years and they gave no trouble until, for some reason or other, there was a rise of terminal temperature. Then there was "trouble to burn."

It will not be argued that all the lubricant used in the air cylinder is deposited on the walls of the receiver, but some of it will be, and the more lubricant used the more will be deposited; and the greater the deposit of lubricant the greater chance for dust to adhere and produce in time the caked masses above referred to. Excess of lubrication, in addition to waste, means increased accumulation of combustible matter, increased lodgment of dust and increased danger of accident. It follows that just as little lubricant should be used as possible, and inasmuch as an air cylinder requires less oil than a cylinder of equal size using steam, the practice on the steam end should not be followed on the air end.

Two lubricants are in general use on air compressor cylinders, a mixture of soap and water and cylinder oil. Either can be made to do the work. The mixture of soap and water has inferior lubricating properties and must be used in quantities greatly in excess of those required of a proper lubricating oil. One case of explosion is reported where soap and water was used almost exclusively. A test of the deposit found in the receiver after the explosion showed that it readily ignited at 400° F. This deposit was 2 ins. thick. The mixture of soap and water was also tested in a laboratory. Upon being evaporated down to a "black, semi-solid mass" it ignited at 500° F. In addition to this soft-soap lubricant there had been used some oil having a burning point of about 400° F. The principal combustible ingredient in the deposit was coal dust. This case

is sufficient to show that the use of soap and water is not a sure preventative of accident. In fact, it goes further and shows that soap and water may not be as good as oil, for the tests showed that it burned readily when dry, and inasmuch as more of it would have to be used than of oil, the deposit of dust would be correspondingly greater. Nevertheless, soap and water may be used to good advantage and provision should be made for its introduction into the cylinder when necessary.

While ignitions are bad enough and to be avoided if possible, explosions are more serious matters. Evidently they are due to the formation of a mixture of a combustible gas or vapor in suitable proportions with air, at a temperature sufficient to ignite. The percentage of gas or vapor required to make an explosive mixture is surprisingly small and in general, the heavier the gas or vapor, the smaller the percentage. This is well shown in the following table, the determinations being made by Dr. P. Eitner, of Carlsruhe:

Table Showing the Low Limit of Explosibility of Certain Gases and Vapors at Normal Temperature and Atmospheric Pressure.

	Per cent. by volume.
Hydrogen	8.5
Marsh Gas	6.3
Ethylene	3.4
Benzene vapor	1.4
Gasolene vapor	1.3
Benzol vapor	1.1

The percentage of combustible gas or vapor required to produce an explosive mixture decreases with the temperature of the mixture. For instance, at ordinary temperatures 16% of carbonic oxide marks the low limit of explosibility; 14.2% at 750° F.; 9.3% at 915° F.; 7.4% at 1,110° F. Furthermore, a mixture non-explosive at low

pressure becomes explosive at higher pressure. If, then, there be a source from which a combustible gas or vapor may be derived, the conditions of pressure and temperature which obtain in the air receiver are favorable to the formation of an explosive mixture with the air. And as shown above, the amount required is very small indeed.

Now, combustible gases or vapors are evolved from all lubricating oils by heat. The lowest temperature at which they begin to come off is called the "flash point" of that oil. At a somewhat higher temperature the gas or vapor will ignite; this is called the "burning point." The flash point of kerosene is usually below 150° F. Ordinary lubricating oils flash at about 250° F. An average of determinations on 40 samples of heavy oils having average flash point of 360° F. gave average burning point of 398° F.; high flash test cylinder oils, from 500° F. to 560° F., gave burning points of 600° to 630° F. The vapors evolved from any of these oils, at the flash point, or the oils themselves, atomized or sprayed, would form an explosive mixture with the suitable percentage of air. From the above table it is evident that as low as 1% by volume would form such a mixture. If the oil were mixed with coal dust the temperature at which such a deposit would evolve a vapor would be the flash point of the oil. It follows that none but high flash test oil should be used in the cylinder.

Makers of cylinder oils claim that some oils have a greater tendency to deposit, or to "carbonize," as they express it, than others, and that the flash point is not necessarily a gage or measure of this "carbonizing" tendency. Lubricating oils are extremely complex chemical combinations of carbon and hydrogen, and it is not at all improbable that oils having the same flash test

would deposit in different degree upon leaving the cylinder. Upon this point, however, no exact data, derived from experiment, have been obtained. The user of the compressor must make his own observations or take the oil manufacturer's word for it.

It is by no means uncommon for the engineer in charge of an air compressor to introduce through the inlet pipe a quantity of light oil, or even kerosene. This is a favorite and sometimes effective way of cleaning dirty discharge valves. Under such circumstances it is possible for an explosion to take place immediately in the cylinder, for the oil, being drawn in in the form of a fine spray or mist, and compressed with the air, produces just the conditions sought after in the cylinder of an oil engine. If an explosion did not occur it would be because the charge "missed fire," the terminal temperature of compression being below the ignition point. That the temperature of compression may rise to the ignition point, and that, too, in very few strokes of the compressor, will be shown later. If an explosion did not occur the light oil or kerosene, having a low flash point, being added to the accumulation of oil and dust already in the receiver, would serve to lower the temperature at which some time in the future a combustible vapor might be evolved. Such practice is simply tempting Providence; and Providence, at times, refuses to resist temptation. Among the cases examined, however, there is not one where the injection of light oil is given as the immediate cause of the accident. It is hardly to be expected that the engineer would report that his ignorance or stupidity caused the trouble. But the use of such oils for such purpose can be fairly characterized as ignorance and stupidity. Considering how serious may be the

results, stronger language would be warranted. If it is necessary to give the cylinder a heavy dose of lubricant on account of dirty valves, when the compressor cannot be shut down for cleaning, soap and water should be used, forced in by an oil pump, with which the cylinder should be equipped, in addition to the regular lubricator.

Special care should be given to the design of discharge valves and clearance spaces, that there may be no small pockets or recesses where oil may accumulate. This also applies to the piping from cylinder to receiver. Bends should be avoided as far as possible, for a change in direction of flow increases the tendency to deposit.

Despite all the care that may be taken as regards lubrication, there remains around collieries the dangers due to the accumulation of coal dust. It is well known that coal dust and air can make an explosive mixture, but it is hardly to be supposed that the air in the receiver could be sufficiently charged with dust to make trouble. Both anthracite and bituminous coals hold varying quantities of combustible gas, mostly marsh gas or "fire damp," in the occluded state, that is, as free gas, not chemically combined. No high temperature, such as is employed in destructive distillation in the manufacture of coal gas, is required to liberate this occluded gas. In a vacuum it may be driven off at the temperature of boiling water. At 300° F. it is readily evolved, with increasing evolution at higher temperatures. Such gas production would be entirely harmless unless a temperature of ignition were reached. But coal dust itself ignites at about 500° F. At this temperature, ignition followed by explosion is to be expected. The evidence in two cases of explosion indicates that this is exactly what occurred. The blame cannot be wholly placed upon the lubricant.

It is responsible only in so far as it enabled the dust to accumulate.

Where a compressor is located near a coal breaker and the air is of necessity heavily dust laden, it would be wise to consider the installation of an air washer. The various methods of air washing cannot be discussed here. Suffice it to say that it need not be an expensive apparatus to operate or maintain, and that in summer time, with a suitable supply of relatively cool water, the reduction in temperature of the inlet air, with consequent increased capacity of the compressor and corresponding saving of power for a given weight of air compressed, would make the air washer an economical device, in addition to greatly reducing the chance of accident.

From the foregoing it would appear that under the best of conditions there is always the possibility of some combustible material accumulating in the discharge pipe and receiver, and under the worst conditions the certainty that the deposit will be excessive. Unless ignited it is harmless. What are the causes that lead to ignition?

TEMPERATURE IN DISCHARGE PIPE AND RECEIVER.

The temperature due to compression depends upon three factors: Initial temperature, before compression; pressure to which the air is compressed; efficiency of cooling devices. No account will be taken of the effect of moisture in the air, and all temperatures given are for dry air.

The initial temperature of a fresh charge of air within the cylinder is always above that of the supply from which it is drawn. It is to be regretted that no accurate means of determining the temperature immedately before compression has been devised. The inlet valves and cylinder

walls are hot from the previous compression stroke, and in coming in contact with these heated surfaces the fresh charge is heated. How serious may be the effect of the rise in initial temperature due to this cause was pointed out by Mr. Julian Kennedy, in a paper on "Blowing Engines," presented before the World's Engineering Congress at Chicago. He said:

> This heating of the incoming air expands it and proportionately reduces the weight of air entering the cylinder at each stroke. I have observed this in the case of an engine which was so constructed as to cause the air to travel about 3 ins. over the hot metal in thin films 3-16-in. thick. Alongside of it was another engine of the same size and make except that valves were used that allowed the air to pass over about 1 in. of metal, the openings being of such size that each stream of air was 2 ins. in thickness. Careful and repeated tests of these engines, when both were in good order, showed that, while the indicator diagrams were practically the same, the one with the large valves would burn about 10% more coke in the furnaces, a result that could only be explained on the supposition that, in the case of the engine with the small air openings, the incoming air, in passing through the small and tortuous passages in the heads, was heated about 25°C. more than in the case of the other engine.

After the above testimony, further comment on the rise of initial temperature due to contact with hot metal surfaces is unnecessarv.

Some rise of initial temperature is frequently attributed to the air in the clearance space, inasmuch as this air is at the temperature of discharge and becomes part of the next cylinder full to be compressed. When air expands without doing work, the slight drop in temperature, known as the Joule-Thomson effect, is insignificant. If, however, it expands against resistance, doing work, its temperature falls, and the fall is proportional to the work done. With mechanically-operated inlet valves, set to open the instant the return stroke started, the clearance air would expand wihout doing work and would serve to raise the initial temperature of the incoming charge.

But this would be inexcusably bad valve setting. With poppet valves, opened by a slight vacuum within the cylinder, the clearance air expands against the piston and does work, and the expansion being very rapid it is presumably adiabatic. Consequently, there is a fall of temperature. In fact, owing to the absorption of some heat while within the clearance space, it is possible that the clearance air, expanding, reaches a lower temperature than that of the charge from which it was derived. In well-designed compressors clearance space is reduced to a minimum, for the sake of capacity, so that, even if there were no drop in temperature of clearance air, the rise of initial temperature due to this cause cannot be serious.

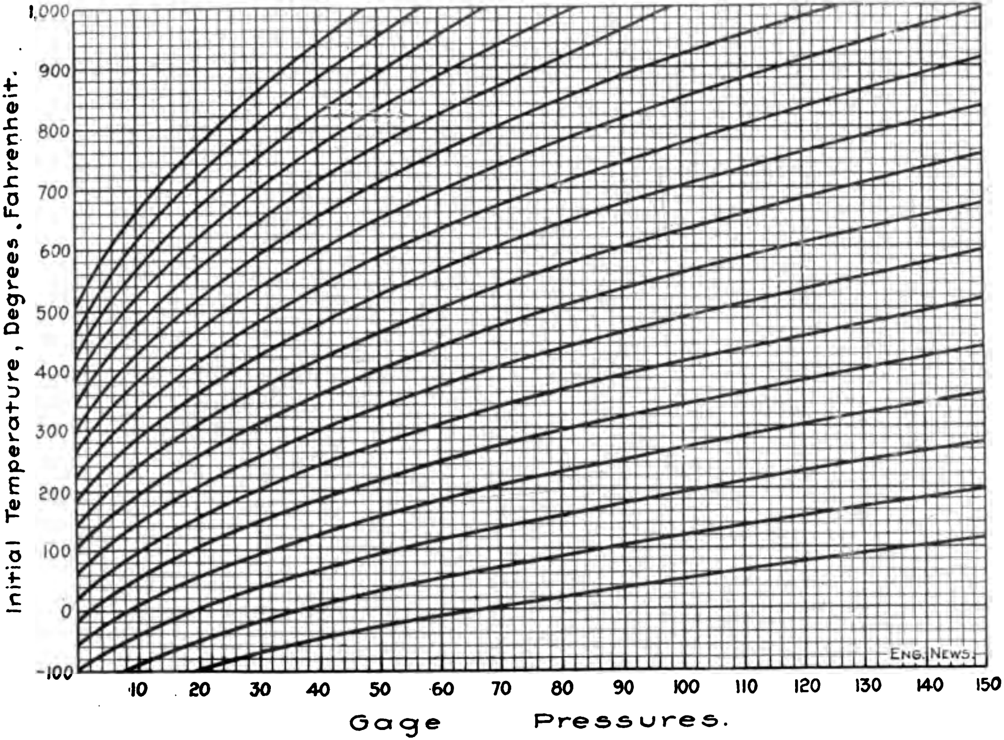
The place from which the air is drawn may have a very important bearing on initial temperature. The engine room is, to be sure, better than the boiler room, as the source of supply, but that is about all that can be said in favor of it. The inlet should be at the coolest and cleanest place available. A difference of 50° between the engine room and the outside air means more than a difference of 50° in terminal temperature, as well as a loss of about 10% in capacity for the same amount of power expended. The report on one explosion makes the recommendation that the air be drawn from an air shaft, cooled with water sprays. Such an arrangement might be adapted to wash the air at the same time.

The effect of leaking discharge valves upon initial temperature and consequently upon the temperature after compression, may be very serious indeed. Suppose an extreme case, where the amount of leakage is just sufficient to maintain atmospheric pressure within the cylinder so that no fresh air enters. The initial temperature

is now nearly the same as the terminal temperature of the previous charge, for the compressed air, in leaking back, has done no work upon the piston, and consequently has not dropped any in temperature. The hot air now receives a second compression, and the terminal temperature, reached by starting from an initial temperature due to the previous stroke, may easily reach the point of ignition of the combustible matter. If the initial temperature were 60° F. and terminal pressure 40 lbs., the terminal temperature, with no cooling, would be 300° F. If this air at 300° F. leaks back and compression starts from that temperature, the temperature of discharge becomes 650° F. With a discharge valve stuck open it is plain that in one stroke of the compressor a temperature might be reached sufficient to ignite the best grade of high flash cylinder oil.

It would be an exceptional case, however, in which the discharge valves leaked so badly that there was no introduction of fresh air at all. Yet to the extent that they do leak is the initial temperature raised. Furthermore, the effect is cumulative, for each rise in initial temperature produces a greater rise in terminal temperature, which, leaking back still further, raises initial temperature, and so on, a sort of endless chain arrangement. In several cases of accident the discharge valves are reported as having been leaking, and in one case an examination was being made at the time the explosion occurred. The results of the examination are not known, for the man was killed. To leaking discharge valves, more than to any other cause, may be attributed the sudden rise of temperature in the receiver, which, with the combustible deposit there, produces an accident.

It is well to note that a given rise in initial tem-



CURVES SHOWING RISE OF TEMPERATURE DUE TO ADIABATIC COMPRESSION OF DRY AIR.
(Initial temperature of curves are taken 40 degrees apart, beginning at 100 degrees below zero.)

perature produces a greater rise in terminal temperature. The accompanying curves show the rise of temperature of dry air, adiabatically compressed, from various initial temperatures to all gage pressures up to 150 lbs. It will be observed that a difference of 40° initial temperature, from 60° F. to 100° F., produces a difference of 72° terminal temperature, at 100 lbs. pressure. This tends further to increase the cumulative effect above referred to as due to leaking discharge valves, for a rise of 1° at the beginning of a stroke involves a rise of nearly 2° at the end when compressing to 100 lbs., single stage.

It will be observed that with single stage compression from 60° F. initial to 80 lbs., without cooling, a temperature of 430° F. is attained. This is a lower initial temperature than generally obtained, yet from what has gone before it is clear that such a terminal temperature is beyond the danger line, even when valves are tight.

The curves also show the rise of temperature with pressure, and make it obvious that, other things being equal, the higher the pressure the greater the likelihood of dangerously high temperatures in the receiver. As a question of fact, there is greater liability to accident at low pressures than at high. If a plant were to be installed to deliver air at 1,000 lbs. pressure, stage compression would be used, the questions of inter and after-cooling very carefully considered, and all precautions taken in design and operation to avoid high temperatures. But in the design, installation and operation of a single stage compressor, working, say, to 40 lbs., such precautions are not taken. The plant does not command respect. Yet, as shown above, in a few strokes, with a sticking discharge valve, a temperature may be attained sufficient to cause everybody

within reach to have a wholesome respect for such a magazine of explosive energy as a receiver may become.

From the foregoing it would appear that all precautions having been taken, we must look for safety from accident to the cooling devices employed to keep down terminal temperatures. Despite all the care that can be taken, some combustible material is sure to accumulate in the receiver. Give it time enough and it will get there. It cannot be expected that discharge valves will forever and always remain tight. Reliance must be placed upon water cooling.

The former practice of injecting water into the air cylinder has been abandoned on modern machines for mechanical reasons. Water jacketing of heads and cylinders on large machines is customary, but such jacketing is entirely insufficient to insure proper cooling. The area of the cool surfaces is so small relative to the volume of air compressed and the time of contact is so short, that the cooling effect is small. But water jacketing is most efficient in keeping down the temperature of the metal in contact with the fresh charge, thus keeping down initial temperature. This, and the aid rendered lubrication by keeping cylinder walls comparatively cool, are the chief services performed by the water jackets. On large machines they cannot be depended upon to absorb the heat of compression. There is too much heat for the time and surface.

Compression by stages, with inter-cooling, with provision for after-cooling in an emergency, are the surest means by which to avoid dangerously high temperatures in the receiver. The curves show the reduction in terminal temperature that may be attained by inter-cooling to any temperature between stages, and inasmuch as for adia-

batic compression, the rise of temperature is proportional to work expended, they also show to what pressure each cylinder should operate in order that each shall do an equal amount of work. Knowing the weight of air compressed per stroke and its specific heat, the curves also give the necessary data from which to calculate the British thermal units to be absorbed by the inter-cooler.

The economies that may be effected by stage compression are well known, but it must be remembered that the economy depends upon the efficiency of the inter-cooler. Without inter-cooling, stage compression effects no economy over single stage. That the inter-cooler may be efficient, it must have ample cooling surface, and it may be remarked here that for the sake of first cost, to cut down the size of the inter-cooler, as is the practice of some manufacturers, is the poorest kind of economy. As well expect to get boiler economy by cutting down heating surface. Economy in both cases depends upon the transference of heat to water, through metal. The amount transferred, other things being equal, depends upon the surfaces in contact.

The after-cooler may be similar in construction to the inter-cooler, or, if water at sufficient pressure is available, it may be a simple water spray so arranged, like a sprinkler head, to throw a fine mist or spray into the discharge pipe. This spray need only be used in an emergency when the temperature in the discharge pipe has risen to the danger point. A steam jet will answer the same purpose, but owing to the latent heat of evaporation, a given weight of water will have greater heat absorptive power than the same weight of steam. Ample provision must be made upon the receiver to drain off this cooling water, but the receiver should have an ample drain anyhow, and be

large enough and so designed as to act as a separator. Only in very exceptional cases would the addition of a cooling spray to the discharge pipe increase the moisture content in the air from the receiver. Usually the air is already at the point of saturation. It cannot be any wetter than it is. This is proven by the fact that water generally accumulates in the receiver. The air is already at the "dew point" and cannot hold any more water at the temperature and pressure. In fact, it is entirely possible to cool the air in the receiver by the addition of water, so that the moisture content will be reduced and the air at the drills or mining machines will be actually dryer than if no water had been added. With a receiver built upon the lines of a steam separator, this result could be readily accomplished, the dangers from explosion practically eliminated, and the troubles due to "freezing up" reduced to a minimum.

Thus we reach the somewhat curious conclusion that the troubles due to heat, namely, ignitions, and the troubles due to cold, namely, "freezing up," may both be greatly alleviated by the same remedy, namely, adequate after-cooling.

If the after-cooling is to be done by a spray and only used when required, it is necessary to install thermometers on discharge pipes, that the temperatures may be observed. Recording thermometers would be preferable for such purposes, but mercury thermometers, with large graduations, reading up to 1,000° F., are not expensive, and would serve the purpose. They should be capable of being read from a distance, and the engineer should watch them as he would a steam gage.

That the liabilitv to ignition and explosion may be reduced to a minimum, the foregoing consider-

ations warrant the following conclusions relative to the design, installation and operation of air compressors:

DESIGN OF COMPRESSORS.—(1) Clearance space should be reduced to a minimum. (2) Ingoing air should traverse as small a surface of hot metal as possible. (3) Discharge valves and passageways should contain no pockets or recesses for the accumulation of oil. (4) Cylinders and heads shoud be water jacketed; in some cases piston water cooling may be resorted to. (5) Stage compression, with adequate inter-cooling, should be employed wherever final pressure and first cost of installation will warrant. (6) Discharge valves must be easy of access for cleaning and examination. There must be no excuse for dirty or leaky valves.

INSTALLATION OF COMPRESSOR.—(1) Air should be drawn from the coolest and cleanest place possible, and never from the engine room. Engine room air is never cool nor clean, and an open intake is a constant invitation to squirt oil in from a can. (2) Around collieries it would be well to consider the washing of the air. (3) A thermometer, preferably recording, should be placed on the discharge pipe. (4) Provision for after-cooling should be made; a water spray will answer, to be used when the thermometer indicates the necessity. (5) The receiver should be provided with a man head for cleaning, and a drain easy of access and ample in size. (6) Automatic sight feed lubricators should be depended upon for regular lubrication, but in addition an oil pump may be installed for the introduction of soap and water in case of necessity.

OPERATION OF THE COMPRESSOR.—(1) High-flash test cylinder oil alone should be used for regular lubrication. Under no circumstances must kerosene or light oil be introduced. If an

extra heavy dose of lubricant is required, give it soap and water through the oil pump. (2) Discharge valves must be kept tight, and to this end the use of the steam engine indicator is advised. The cards may not tell much about the condition of the valves, but one of the greatest values of the indicator is the moral effect upon the engineer. (3) Discharge valves should be cleaned from dust and oil and frequent examinations made to see if they need it. (4) Accumulation of water and oil must be blown from the receiver and an internal examination made at stated intervals. (5) The thermometer should be watched like a steam gage. Before it reaches 400° F. get busy. This is the danger limit. Put on the after-cooling spray, examine all water supply pipes and the discharge valves. (6) After the designer has done all in his power to make a perfect machine, and after the purchaser has taken all reasonable precautions to install it with every safeguard against accident, the responsibility must rest on the engineer in charge. He should be thoroughly instructed as to the possibility of explosion, the dangers attendant upon the use of any but the prescribed oil, and the effect of leaking discharge valves. He should be instructed in the use of the steam engine indicator and required to submit cards at stated intervals. He should record in the engine room log the daily condition of the machines under his charge. He should be given a wholesome respect for an air compressor, with imperative instructions to keep it clean, inside as well as out.

It may be objected that some expense is involved in following all the above recommendations and suggestions. In the preparation of this paper about twenty different concerns have been found that have learned from experience that explosions and ignitions are expensive. Very many more could give the same testimony.